JOURNAL OF PLANT PROTECTION RESEARCH Vol. 52, No. 4 (2012)

# MEASUREMENT AND CLASSIFICATION METHODS USING THE ASAE S572.1 REFERENCE NOZZLES

*Bradley Keith Fritz*[1], *Wesley Clint Hoffmann*[1], *Zbigniew Czaczyk*[1]*, *William Bagley*[2], *Greg Kruger*[3], *Ryan Henry*[3]

[1] United States Department of Agriculture Agricultural Research Service, 2771 F&B Road, College Station, Texas 77845, USA
[2] Wilbur-Ellis, 4396 East Evans Road, San Antonio, Texas 75289, USA
[3] University of Nebraska, 402 West State Farm Road, North Platte, Nebraska 69101, USA

*Received: July 31, 2012*
*Accepted: September 17, 2012*

**Abstract:** An increasing number of spray nozzle and agrochemical manufacturers are incorporating droplet size measurements into both research and development. Each laboratory invariably has their own sampling setup and procedures. This is particularly true about measurement distance from the nozzle and concurrent airflow velocities. Both have been shown to significantly impact results from laser diffraction instruments. These differences can be overcome through the use of standardized reference nozzles and relative spray classification categories. Sets of references nozzles, which defined a set of classification category thresholds, were evaluated for droplet size under three concurrent air flow velocities (0.7, 3.1 and 6.7 m/s). There were significant, though numerically small, differences in the droplet size data between identical reference nozzles. The resulting droplet size data were used to categorize a number of additional spray nozzles at multiple pressure and air flow velocities. This was done to determine if similar classifications were given across the different airspeeds. Generally, droplet size classifications agreed for all airspeeds, with the few that did not, only differing by one category. When reporting droplet size data, it is critical that data generated from a set of reference nozzles also be presented as a means of providing a relative frame of reference.

**Key words**: Droplet size, droplet size measurement, laser diffraction, reference nozzle, spray classification

## INTRODUCTION

Spray droplet size is arguably one of the primary factors influencing both on- and off-target deposition of applied sprays (Hewitt 2000; Hewitt *et al.* 2002). The ability to evaluate the effect that both spray nozzles and tank mix adjuvants have on the resulting drop size is critical. There are a number of options for measuring droplet size, each with their own requirements in terms of sampling methods and data processing. It has long been recognized that these different systems and the methods used to measure droplet size can influence the results (Tishkoff 1984; Dodge 1987; Dodge *et al.* 1987; Young and Bachalo 1988; Arnold 1990). A growing number of laboratories are incorporating droplet size measurements into both research and development of agrochemical technologies. Each laboratory has invariably developed their own sampling setup and protocols with ranges in both sampling distance from the nozzle and concurrent airflow velocities (Elsik 2011). Both have been shown to significantly impact the droplet sizing results from laser diffraction instruments, with concurrent air velocities less than 6.7 m/s over-estimating the volume fraction of the smaller end of the spray (Young and Bachalo 1988; Arnold 1990 and Elsik 2011). One method of addressing these interlaboratory differences is by using standardized spray nozzles as relative measures for classifying other nozzles or spray formulations.

The initial proposed reference nozzle classification scheme was that proposed in the British Crop Protection Council (BCPC) Conference. It was noted that there needed to be an easier way to signify spray quality differences. This differences between different nozzles and spray pressures should provide a better understanding of both efficacy and should also addressed droplet size measurement differences seen between different systems and methods (Doble *et al.* 1985). Doble *et al.* (1985) stated that median droplet size $D_{v0.5}$, which signifies 50% volume median droplet diameter (VMD), is not a sufficient descriptor as a recent BCPC round robin showed a 40% variation between participating labs. A standardize reference set of nozzles were selected which demarked midpoints between five size classes: Very Fine, Fine, Medium, Coarse and Very Coarse (VF, F, M, C and VC, respectively). The Medium classification was denoted as the "reference" category, or the typically accepted practice for arable spraying. These reference nozzle classification curves

*Corresponding address:
zbicza@gmx.net

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| 1. REPORT DATE | 2. REPORT TYPE | 3. DATES COVERED |
|---|---|---|
| **2012** | | **00-00-2012 to 00-00-2012** |

4. TITLE AND SUBTITLE
**Measurement and Classification Methods Using the ASAE S572.1 Reference Nozzles**

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
**US Department of Agriculture,Agricultural Research Service,2771 F&B Road,College Station,TX,77845**

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT
**An increasing number of spray nozzle and agrochemical manufacturers are incorporating droplet size measurements into both research and development. Each laboratory invariably has their own sampling setup and procedures. This is particularly true about measurement distance from the nozzle and concurrent airflow velocities. Both have been shown to significantly impact results from laser diffraction instruments. These differences can be overcome through the use of standardized reference nozzles and relative spray classification categories. Sets of references nozzles, which defined a set of classification category thresholds, were evaluated for droplet size under three concurrent air flow velocities (0.7, 3.1 and 6.7 m/s). There were significant, though numerically small, differences in the droplet size data between identical reference nozzles. The resulting droplet size data were used to categorize a number of additional spray nozzles at multiple pressure and air flow velocities. This was done to determine if similar classifications were given across the different airspeeds. Generally, droplet size classifications agreed for all airspeeds, with the few that did not, only differing by one category. When reporting droplet size data, it is critical that data generated from a set of reference nozzles also be presented as a means of providing a relative frame of reference.**

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT **unclassified** | b. ABSTRACT **unclassified** | c. THIS PAGE **unclassified** | **Same as Report (SAR)** | **11** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

were later changed from midpoints of the categories to the thresholds of each (Southcombe *et al.* 1997).

Following the BCPC classification scheme, the American Society of Agricultural and Biological Engineers (ASABE, former ASAE) developed a similar scheme that eventually became the standard ASAE S572.1 "Spray Nozzle Classification by Droplet Spectra" (ASAE 2009). In response to the initial development of this standard, the variation in droplet size measurements for reference sprays was examined both for similar nozzles from different manufacturers (Womac *et al.* 1999) and for "identical" nozzles from the same manufacturer (Womac 2000). The comparison of nozzle droplet size data was obtained using a laser diffraction instrument (30 cm measurement distance with the nozzle operating in still air). Differences were found between similar nozzles from different manufacturers (ranging from 5 to 75 μm), while coefficients of variation (standard deviation over the mean) of less than 4% were found within a given manufacturer's nozzles (Womac *et al.* 1999). When a larger sample of given manufacturer's nozzles were tested, mean spreads (difference between maximum and minimum over the mean) between 10, 50, and 90% volume diameters ($D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$, respectively) were 13.0, 8.6, and 12.8%, respectively (Womac 2000). From these larger sets of nozzles, five dedicated reference sets for the new S572.1 standard were identified. However, standard deviations of measured $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ values still ranged from 0.36 to 3.66 μm, 0.44 to 5.87 μm, and 2.6 to 32.5 μm, respectively (Womac 2000). As a result of both of these studies, it was concluded that the process of classifying nozzles is dynamic and needs to be maintained on a regular basis. In this way an ensured, repeatable standard will be available and used (Womac 2000).

The present version of the nozzle classification standard has two stated objectives. They are the relative comparison of a nozzle to standardized references, and to provide users with droplet size data as an indication of potential spray drift and efficacy (ASAE 2009). Spray size categories range from Extremely Fine to Ultra Coarse, with nozzles, flow rates, and pressures specified for each. The standard further specifies the use of water for reference nozzle measurements. A water-surfactant mixture, though, should be used for spray drift reduction nozzles or nozzles with pre-orifices or internal turbulence chambers (ASAE 2009). Measurements are to be made using laser-based instruments where the distance between the measurement point and nozzle discharge ranges from 200 to 500 mm (8 and 20 in) and the nozzles operate in still air (ASAE 2009). The resulting means of the reference nozzles $D_{v0.1}$, $D_{v0.5}$ and $D_{v0.9}$ plus one standard deviation, define the upper threshold for each category (ASAE 2009).

Regardless of the stated objective of the ASABE classification standard – regarding drift potential based on the previous research and literature surrounding this issue, the main intent is to provide a method by which different labs can compare droplet sizes from nozzles and spray solutions of interest. The use of a relative classification scheme based on a set of reference sprays is used. The reference nozzles also allow for relative comparisons of nozzles operating at different conditions, for changes in droplet size classification (Czaczyk 2012). The assumption is that a nozzle and/or spray formulation evaluated under one set of laboratory practices and given a classification will receive the same classification from any other laboratory. The treatment will be regardless of actual numerical droplet size values reported. A recent round robin study illustrated the potential differences in numerical droplet size data that exist between labs in which the labs use different evaluation protocols. Five labs, all using laser diffraction, but with differing coaxial air flows (four at 0.7 m/s or less and one at 3 m/s), evaluated droplet size for a series of nozzles and spray formulations (Elsik 2011). Labs using concurrent airflow of 3 m/s reported consistently larger droplet sizes and smaller percent volumes of less than 105 μm than the other labs (Elsik 2011). This is consistent with earlier work and was documented previously by a Spray Drift Task Force (SDTF) study (1997). This study noted that spatial bias from laser diffraction results diminishes with higher air flows. Only one set of reference nozzle curve data with water, was presented by Elsik (2011). The study gave no indication of which lab generated the data. Ideally each lab participating in the study would have generated their own set of unique reference curves, and assigned categories to the other measured data. Potentially, this information would have resulted in all labs returning similar spray quality classifications for each treatment tested. At the time this work was prepared, a literature review did not return any published work documenting inter-laboratory evaluations of either nozzles or spray formulations using either the BCPC or ASABE spray classification standards. Such a lack of accountability means that evaluation nozzles using different measurement setups and protocols resulted in the same assigned spray quality category.

The first objective of this work was to generate sets of reference nozzle data across several typical concurrent airflow velocities and evaluate a number of additional nozzles and pressures at each. The second objective was to compare spray quality classifications between methods. Most of the groups involved in this work have adopted laser diffraction instruments with measurement distances falling in the recommended 200 to 500 mm range, while coaxial air velocities range from still air to 6.7 m/s or greater. Previous research has demonstrated that concurrent airflow velocity alters droplet velocity at the point of measurement. Therefore, the resulting droplet size reported is affected. However, as stated earlier, no published data was found demonstrating that the relative classification scheme accounts for the different measurement protocols.

## MATERIALS AND METHODS

Briefly, sets of ASAE S572.1 (ASAE 2009) reference nozzles were evaluated for droplet size in low speed wind tunnel trials at three concurrent air velocities. Three nozzles for each category were selected based on specified flow rate. The nozzles were evaluated for droplet size using laser diffraction. Thirteen additional nozzles, each at two spray pressures, were also evaluated for droplet size and spray quality category at each concurrent air velocity. Spray quality categories were then compared for each.

**Operational Setup – Nozzles and Wind Tunnel**

All testing was conducted in the United States Department of Agriculture, Agricultural Research Service (USDA ARS) using the Aerial Application Technology (AAT) group's low speed wind tunnel (1.2x1.2x12.2 m). The operational air speed range of the tunnel is from 0 to 8 m/s generated from an axial flow fan, with an air flow rate 0 to 600 $m^3$/min. A corrugated flow straightener is positioned 1.2 m downstream of the fan. A plumbed nozzle body was fixed so the nozzle discharge point was 30 cm upstream of the measurement point. The nozzle body was secured on a vertical traverse allowing for the full spray cloud to be traversed through the laser. Nozzles were plumbed (minimum 6.4 mm inner diameter tubing and fittings) to 19 l capacity stainless steel pressure tanks which were pressurized using an air compressor. A pressure regulator was used to adjust and maintain pressure. An electronic pressure transducer (Model PX409-100GUSB, Omega Engineering Inc., Stamford, CT) that was positioned 20 cm from nozzle outlet, was used to measure pressure. During all spray trials the relative temperature difference between the spray solution and the ambient air was no more than 5 K.

All reference nozzles were stainless steel flat fans from the Spraying Systems Co. (Wheaton, IL). Specifically, the TeeJet 11001, 11003, 11006, 8008, 6510 and 6515 flat fans corresponded to the spray category thresholds Very Fine/Fine (VF/F), Fine/Medium (F/M), Medium/Coarse (M/C), Coarse/Very Coarse (C/VC), Very Coarse/Extremely Coarse (VC/XC) and Extremely Coarse/Ultra Coarse (XC/UC), respectively. Three nozzles were selected for each spray category based on measured flow rate and pressure. All nozzle flow rating was done in place using the same plumbing and positioning used for wind tunnel droplet sizing work. Flow rate for each nozzle was measured by placing the pressured spray vessel, which contained water, on an electronic load cell (Model PUF-100-015-2, Loadstar Sensors, Fremont, CA). The load cell was operated via USB connectivity to a computer that allowed for tarring the scale prior to each flow rate measurement. Spray was activated and allowed to operate for sixty seconds after which it was shut off and the total weight loss recorded. Flow rate was converted to liters per minute by dividing the total weight lost by the density of water (1 kg/l). Nozzles were accepted if flow rate and pressure matched that specified by ASAE S572.1 (ASAE 2009). For the largest size classification, Ultra Coarse (UC), the pressure had to be increased from the specified 150 kPa (21.7 psi) to 200 kPa (29 psi) to get the specified flow rate. The authors conjecture that the lower flow rate did not sufficiently open the nozzle body check valve, which is activated at 103 kPa (15 psi), to provide sufficient flow. Once three acceptable nozzles for each category were selected, droplet size measurements were made with the described setup at concurrent airflow velocities of 0.7, 3.1 and 6.7 m/s (1.5, 7 and 15 mph) using both water and water plus 0.25% v/v non-ionic surfactant (NIS) R11 (Wilbur-Ellis, Fresno, CA) with dynamic surface tension dST ~32 mN/m. Though ASAE S572.1 specifies that only water be used for the reference nozzles, the authors have used the water plus NIS as a "blank" for simulating active product and generated references curves. Using the "blank" provided a more realistic category rating, particularly as it relates to providing an indication of drift potential compared to tap water only (dST ~62 mN/m).

Thirteen additional nozzles were also evaluated for droplet size at spray pressures of 207 and 414 kPa (30 and 60 psi) at all three airspeeds using water plus 0.25% v/v R11. Four Spraying Systems TeeJet nozzles: AIXR 11003, AITT 11003, AI 11003VS and a TT 11006VP, one Albuz ceramic nozzle: AVI ISO 11003 (CoorsTek, Golden, CO), one Lechler nozzle LU 11003 POM (St. Charles, IL), three Hypro nozzles: GAT 11003, FC-GA 11003 and FC-TR 11003 (New Brighton, MN), one Hardi nozzle: MD 11003 (Hardi North America, Davenport, IA), and three Delavan disc core nozzle with swirl plates: D3-25, D5-25 and D8-45 (Delavan Spray Technologies, Monroe, NC).

**Laser Diffraction System – Sympatec HELOS**

A Sympatec HELOS laser diffraction system (Sympatec Inc., Clausthal, Germany) was used for all droplet size measurements. The Helos system utilizes a 623 nm He–Ne laser and was fitted with a lens (denoted by manufacturer as R7) with a dynamic size range of 0.5 to 3 500 μm. Throughout the testing, it was insured that no droplets were detected in bins within three channels of the first damped channel. A minimum of three replicate measurements were made with each replication being a complete traverse of the nozzle vertically through the laser. Averages and standard deviations for the 10, 50 and 90% volume diameters and the percent spray volume with a diameter less than 100 μm: $V_{<100}$ (% volume) were determined and reported.

## RESULTS

**Reference Nozzle Flow Rates**

Reference nozzle flow rates and pressures, for the selected three nozzles, match those specified by ASAE S572.1 (ASAE 2009), with the exception of the 6515 nozzles which all had flow rates of 4.36 l/min at the specified 150 kPa. To reach the targeted flow rate of 4.92 l/min, spray pressure had to be increased to 200 kPa. As mentioned earlier, the authors conjecture that the combination of the lower pressure and the activation pressure of the nozzle body check value likely did not allow for full flow at the specified pressure. While only three nozzles for each category are shown in table 1, in most cases, at least one or two additional nozzles were tested that did not match the standard flow rates and pressures.

**Reference Nozzle Droplet Sizes**

Droplet size data (means ± standard deviations) for each nozzle within each classification category for each measurement airspeed and for both water only (Tables 2, 3, 4), and water plus NIS (Tables 5, 6, 7) are given below. It should be noted that the reference nozzles selected were not certified by Spraying Systems. This means that absolute droplet sizes and ratings may be different from an official calibrated set of nozzles. While the authors did not have access to an official set of reverence nozzles at

Table 1. Reference nozzle flow rates for the three selected nozzles used in droplet size testing

| Nozzle type | Number of nozzle | Pressure [kPa] | Flow rate [l/min] measured | reference |
|---|---|---|---|---|
| | 1 | | 0.47 | |
| 11001 | 2 | 450 | 0.48 | 0.48 |
| | 3 | | 0.48 | |
| | 1 | | 1.20 | |
| 11003 | 2 | 300 | 1.19 | 1.18 |
| | 3 | | 1.18 | |
| | 1 | | 1.93 | |
| 11006 | 2 | 200 | 1.93 | 1.93 |
| | 3 | | 1.93 | |
| | 1 | | 2.84 | |
| 8008 | 2 | 250 | 2.87 | 2.88 |
| | 3 | | 2.87 | |
| | 1 | | 3.23 | |
| 6510 | 2 | 200 | 3.25 | 3.22 |
| | 3 | | 3.20 | |
| | 1 | | 4.94 | |
| 6515 | 2 | 200 | 4.91 | 4.92 |
| | 3 | | 5.00 | |

the time of this testing the relative ratings and comparisons between measurements methods presented here are still valid. While there are cases of significant differences in measured droplet size parameters between the three nozzles selected for each spray category, for the most part these differences are numerically small. However, there are a few cases where the difference is 10 to 20 μm. This is not surprising given the previous work by Womac (2000) who found even greater differences when testing a larger subset of similar nozzles. From this larger subset (15 to 49 nozzles), a set of five nozzles that fell in the midpoint of the measured droplet size parameters, were selected as dedicated reference nozzles (Womac 2000). For this work, though, the three nozzles tested were selected from a larger set of six based on flow rate alone, as discussed previously. Obtaining an official calibrated set of reference nozzles from Spraying Systems would insure that the reference curves are representative of those the standards were based on. With that in mind, the data from all three nozzles within each category were averaged to generate a set of reference spray category threshold curves (Table 8 for water only and Table 9 for water plus 0.25% v/v NIS R11).

Table 2. Droplet size data for the water only spray solution measured at a concurrent air flow velocity of 0.7 m/s for each of the three individual nozzles within each reference droplet size category

| Nozzle | No. | $D_{v0.1}$* mean ±standard deviation [μm] | $D_{v0.5}$* mean ±standard deviation [μm] | $D_{v0.9}$* mean ±standard deviation [μm] | $V_{<100}$* [$\%_{vol}$] |
|---|---|---|---|---|---|
| | 1 | 49.1±2.0 a | 116.7±0.2 b | 199.1±1.2 a | 37.3±0.1 a |
| 11001 | 2 | 47.7±1.5 a | 116.4±0.6 ab | 197.8±1.2 a | 37.4±0.3 a |
| | 3 | 48.3±0.8 a | 115.5±0.4 a | 200.0±1.0 a | 38.2±0.3 b |
| | 1 | 82.1±0.4 a | 188.7±1.4 a | 364.8±3.2 b | 15.8±0.2 a |
| 11003 | 2 | 82.5±0.1 a | 189.6±0.7 a | 365.2±1.0 b | 15.7±0.0 a |
| | 3 | 82.7±0.8 a | 187.7±1.4 a | 359.2±0.9 a | 15.6±0.3 a |
| | 1 | 108.0±0.4 b | 285.0±0.6 c | 558.3±0.8 a | 8.2±0.1 a |
| 11006 | 2 | 107.4±0.9 b | 282.0±1.5 b | 552.0±4.5 a | 8.3±0.2 a |
| | 3 | 105.3±0.1 a | 275.5±0.3 a | 552.6±2.9 a | 8.8±0.0 b |
| | 1 | 128.2±5.6 a | 353.3±2.6 a | 675.2±2.2 a | 5.2±1.0 a |
| 8008 | 2 | 131.2±0.8 a | 355.6±1.7 a | 669.1±1.9 a | 4.6±0.1 a |
| | 3 | 131.0±0.5 a | 353.5±0.6 a | 669.8±3.1 a | 4.6±0.1 a |
| | 1 | 150.2±0.8 a | 432.4±1.2 b | 809.4±1.0 b | 3.5±0.0 a |
| 6510 | 2 | 147.1±1.5 a | 423.8±0.7 a | 789.6±1.5 a | 3.6±0.1 a |
| | 3 | 148.7±2.0 a | 426.3±2.2 a | 793.8±7.6 a | 3.5±0.1 a |
| | 1 | 196.1±0.4 b | 572.4±1.9 b | 1112.1±22.6 a | 2.1±0.0 a |
| 6515 | 2 | 185.7±3.5 a | 558.2±4.9 a | 1105.5±22.2 a | 2.4±0.1 b |
| | 3 | 202.3±1.4 c | 578.8±3.0 b | 1128.6±9.0 a | 2.0±0.1 a |

*means within each nozzle type and droplet size parameter grouping ($D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, $V_{<100}$) followed by the same letter are not significantly different as determined using SYSTAT (Version 13, Systat Software INC., Chicago, IL)

Table 3. Droplet size data for the water only spray solution measured at a concurrent air flow velocity of 3.1 m/s for each of the three individual nozzles within each reference droplet size category

| Nozzle | No. | $D_{v0.1}$* | $D_{v0.5}$* | $D_{v0.9}$* | $V_{<100}$* |
|---|---|---|---|---|---|
| | | mean ±standard deviation [µm] | | | [$\%_{vol}$] |
| 11001 | 1 | 59.5±0.6 a | 124.7±0.2 a | 212.5±0.6 a | 33.2±0.1 b |
| | 2 | 60.4±0.6 a | 126.7±0.4 b | 214.5±0.2 b | 32.2±0.3 a |
| | 3 | 59.9±0.2 a | 124.5±0.3 a | 210.0±0.1 a | 33.3±0.1 b |
| 11003 | 1 | 95.4±0.5 a | 221.3±0.8 a | 390.6±1.5 b | 11.2±0.1 b |
| | 2 | 96.2±0.1 b | 223.4±0.8 b | 391.6±1.3 b | 10.9±0.0 a |
| | 3 | 95.0±0.4 a | 221.1±0.4 a | 387.1±0.1 a | 11.2±0.1 b |
| 11006 | 1 | 132.2±1.0 b | 331.0±1.6 b | 584.8±3.2 a | 5.2±0.1 a |
| | 2 | 133.0±0.6 b | 332.2±1.0 b | 588.5±0.5 b | 5.1±0.1 a |
| | 3 | 128.7±0.6 a | 322.1±1.1 a | 580.4±3.9 a | 5.5±0.1 b |
| 8008 | 1 | 149.3±0.8 a | 380.2±1.1 b | 695.7±3.1 b | 4.1±0.1 a |
| | 2 | 149.7±0.8 a | 381.8±0.8 b | 695.5±1.6 b | 4.1±0.0 a |
| | 3 | 148.6±0.7 a | 377.7±0.9 a | 685.8±3.1 a | 4.1±0.0 a |
| 6510 | 1 | 178.5±0.3 b | 459.6±0.4 b | 833.3±2.6 b | 2.9±0.0 a |
| | 2 | 175.9±0.9 a | 451.6±0.3 a | 813.8±2.1 a | 3.0±0.1 b |
| | 3 | 178.1±1.0 b | 455.2±3.1 b | 814.7±9.7 a | 2.9±0.0 a |
| 6515 | 1 | 244.9±1.5 a | 615.8±5.4 b | 1172.9±12.9 a | 1.5±0.0 a |
| | 2 | 239.0±0.4 b | 605.4±1.5 a | 1174.1±3.5 a | 1.6±0.0 b |
| | 3 | 245.2±2.2 a | 612.8±2.4 ab | 1166.4±7.2 a | 1.5±0.0 a |

*means within each nozzle type and droplet size parameter grouping ($D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, $V_{<100}$) followed by the same letter are not significantly different as determined using SYSTAT (Version 13, Systat Software INC., Chicago, IL)

Table 4. Droplet size data for the water only spray solution measured at a concurrent air flow velocity of 6.7 m/s for each of the three individual nozzles within each reference droplet size category

| Nozzle | No. | $D_{v0.1}$* | $D_{v0.5}$* | $D_{v0.9}$* | $V_{<100}$* |
|---|---|---|---|---|---|
| | | mean ±standard deviation [µm] | | | [$\%_{vol}$] |
| 11001 | 1 | 62.2±0.2 b | 134.6±0.1 c | 231.2±1.5 b | 29.4±0.1 a |
| | 2 | 61.4±1.0 ab | 132.0±0.3 b | 226.4±1.7 b | 30.4±0.2 b |
| | 3 | 57.0±0.3 a | 125.1±0.2 a | 214.4±1.2 a | 33.6±0.1 c |
| 11003 | 1 | 106.1±0.3 b | 241.6±0.4 a | 406.0±0.7 b | 8.7±0.1 a |
| | 2 | 106.6±0.4 b | 243.2±0.5 b | 407.9±0.5 c | 8.6±0.1 a |
| | 3 | 105.3±0.3 a | 240.7±0.6 a | 403.9±0.7 a | 8.8±0.1 b |
| 11006 | 1 | 156.6±0.8 b | 358.6±2.3 b | 614.4±2.5 b | 3.5±0.0 a |
| | 2 | 156.0±0.5 b | 358.1±1.5 b | 608.7±6.1 b | 3.5±0.0 a |
| | 3 | 149.2±0.9 a | 346.0±2.0 a | 594.0±2.9 a | 4.0±0.0 b |
| 8008 | 1 | 173.1±1.1 a | 399.9±1.6 a | 704.6±6.2 a | 2.8±0.1 a |
| | 2 | 173.6±0.9 a | 402.6±0.9 a | 710.5±0.7 a | 2.8±0.0 a |
| | 3 | 173.5±0.2 a | 400.7±0.5 a | 710.4±2.1 a | 2.8±0.0 a |
| 6510 | 1 | 210.5±0.1 b | 484.8±1.0 b | 847.8±2.7 a | 1.9±0.0 a |
| | 2 | 207.8±1.4 a | 480.4±1.0 a | 844.1±4.9 a | 1.9±0.0 a |
| | 3 | 209.3±1.0 ab | 482.2±0.6 ab | 845.8±2.1 a | 1.9±0.0 a |
| 6515 | 1 | 291.6±2.6 b | 652.7±7.4 a | 1170.5±34.5 a | 0.8±0.0 a |
| | 2 | 286.8±1.7 a | 651.5±5.8 a | 1206.9±14.8 a | 0.8±0.0 a |
| | 3 | 291.5±0.4 b | 655.5±1.4 a | 1185.8±10.7 a | 0.8±0.0 a |

*means within each nozzle type and droplet size parameter grouping ($D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, $V_{<100}$) followed by the same letter are not significantly different as determined using SYSTAT (Version 13, Systat Software INC., Chicago, IL)

Table 5. Droplet size data for the water plus 0.25% v/v NIS spray solution measured at a concurrent air flow velocity of 0.7 m/s for each of the three individual nozzles within each reference droplet size category

| Nozzle | No. | $D_{v0.1}$* | $D_{v0.5}$* | $D_{v0.9}$* | $V_{<100}$* |
|---|---|---|---|---|---|
| | | mean ±standard deviation [µm] | | | [$\%_{vol}$] |
| 11001 | 1 | 31.4±11.5 ab | 115.2±0.5 c | 194.1±2.4 a | 38.1±0.4 a |
| | 2 | 26.1±2.4 a | 114.3±0.1 b | 192.4±0.8 a | 39.0±0.1 b |
| | 3 | 45.6±0.6 b | 113.2±0.2 a | 195.1±1.1 a | 39.9±0.1 c |
| 11003 | 1 | 76.4±1.5 a | 172.7±2.3 a | 335.4±2.1 a | 18.4±0.7 a |
| | 2 | 76.6±1.0 a | 173.2±2.0 a | 335.1±1.5 a | 18.2±0.5 a |
| | 3 | 76.5±0.3 a | 172.0±0.9 a | 333.3±1.4 a | 18.3±0.1 a |
| 11006 | 1 | 99.1±0.7 b | 245.2±2.0 b | 499.1±5.6 b | 10.2±0.2 a |
| | 2 | 96.0±1.0 ab | 237.3±1.0 ab | 488.4±1.6 ab | 11.0±0.3 ab |
| | 3 | 93.6±2.0 a | 225.3±8.1 a | 475.1±9.6 a | 11.7±0.6 b |
| 8008 | 1 | 110.0±0.8 a | 301.1±1.9 b | 594.0±3.2 a | 7.9±0.1 a |
| | 2 | 109.7±0.3 a | 302.1±0.8 b | 604.0±2.9 b | 8.0±0.1 a |
| | 3 | 108.8±0.6 a | 296.1±1.7 a | 592.1±1.3 a | 8.1±0.1 a |
| 6510 | 1 | 130.0±0.0 a | 360.1±1.8 b | 717.6±4.5 a | 4.7±0.0 a |
| | 2 | 128.6±0.3 a | 352.3±0.3 a | 710.1±2.1 a | 4.7±0.0 a |
| | 3 | 125.7±5.3 a | 350.1±4.5 a | 712.0±4.4 a | 5.3±1.0 a |
| 6515 | 1 | 155.0±0.7 b | 463.1±3.1 b | 1052.1±27.2 b | 2.9±0.1 a |
| | 2 | 144.9±0.9 a | 428.3±4.4 a | 978.7±7.9 a | 3.4±0.0 c |
| | 3 | 152.2±1.5 b | 451.9±4.3 b | 989.1±6.0 A | 3.1±0.0 b |

*means within each nozzle type and droplet size parameter grouping ($D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, $V_{<100}$) followed by the same letter are not significantly different as determined using SYSTAT (Version 13, Systat Software INC., Chicago, IL)

Table 6. Droplet size data for the water plus 0.25% v/v NIS spray solution measured at a concurrent air flow velocity of 3.1 m/s for each of the three individual nozzles within each reference droplet size category

| Nozzle | No. | $D_{v0.1}$* | $D_{v0.5}$* | $D_{v0.9}$* | $V_{<100}$* |
|---|---|---|---|---|---|
| | | mean ±standard deviation [µm] | | | [$\%_{vol}$] |
| 11001 | 1 | 57.5±0.5 a | 123.2±0.3 b | 210.3±1.0 b | 34.4±0.2 a |
| | 2 | 56.1±0.4 a | 120.5±0.8 a | 206.0±0.9 a | 35.7±0.4 b |
| | 3 | 56.2±1.5 a | 121.5±0.4 a | 208.4±0.9 b | 35.3±0.2 b |
| 11003 | 1 | 88.1±0.3 ab | 203.6±0.4 a | 358.6±0.8 ab | 13.5±0.1 ab |
| | 2 | 88.4±0.4 b | 204.1±0.6 a | 359.2±0.5 b | 13.4±0.2 a |
| | 3 | 87.6±0.2 a | 203.1±0.4 a | 357.7±0.4 a | 13.7±0.1 b |
| 11006 | 1 | 113.0±1.2 b | 285.3±2.6 c | 534.2±4.3 a | 7.4±0.2 a |
| | 2 | 112.3±0.5 b | 279.7±1.3 b | 521.5±1.5 a | 7.5±0.1 a |
| | 3 | 108.1±0.6 a | 271.5±0.3 a | 522.3±7.9 a | 8.2±0.1 b |
| 8008 | 1 | 126.0±0.5 ab | 326.8±2.1 a | 610.9±6.5 ab | 5.8±0.0 ab |
| | 2 | 126.8±0.1 b | 329.2±0.8 a | 624.1±1.4 b | 5.7±0.0 a |
| | 3 | 125.4±0.7 a | 325.7±1.1 a | 609.8±2.1 a | 5.9±0.1 b |
| 6510 | 1 | 142.3±0.4 b | 385.9±0.2 b | 759.2±1.1 b | 4.4±0.1 a |
| | 2 | 140.8±0.5 a | 381.5±0.5 a | 743.6±8.9 a | 4.5±0.1 a |
| | 3 | 140.3±0.5 a | 380.3±0.7 a | 738.7±2.3 a | 4.5±0.1 a |
| 6515 | 1 | 181.2±0.8 c | 493.9±3.0 c | 1051.6±21.1 b | 2.4±0.0 a |
| | 2 | 170.0±1.0 a | 473.0±0.7 a | 1067.7±16.2 b | 2.8±0.1 c |
| | 3 | 177.0±1.8 b | 483.3±2.8 b | 1010.6±6.3 a | 2.5±0.1 b |

*means within each nozzle type and droplet size parameter grouping ($D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, $V_{<100}$) followed by the same letter are not significantly different as determined using SYSTAT (Version 13, Systat Software, INC., Chicago, IL)

Table 7. Droplet size data for the water plus 0.25% v/v NIS spray solution measured at a concurrent air flow velocity of 6.7 m/s for each of the three individual nozzles within each reference droplet size category

| Nozzle | No. | $D_{v0.1}$* | $D_{v0.5}$* | $D_{v0.9}$* | $V_{<100}$* |
|---|---|---|---|---|---|
| | | mean ±standard deviation [μm] | | | [$\%_{vol}$] |
| 11001 | 1 | 55.1±0.9 a | 123.0±1.2 a | 222.5±5.7 a | 35.1±0.6 c |
| | 2 | 57.0±0.4 b | 128.2±0.3 b | 224.6±0.9 ab | 32.7±0.2 b |
| | 3 | 58.2±0.3 b | 130.7±0.5 c | 232.2±1.9 b | 31.8±0.2 a |
| 11003 | 1 | 96.2±0.6 a | 222.0±0.9 a | 378.7±1.3 a | 10.9±0.1 a |
| | 2 | 95.6±0.4 a | 221.1±1.1 a | 378.4±2.7 a | 11.0±0.1 a |
| | 3 | 94.8±1.2 a | 220.1±2.2 a | 375.6±2.8 a | 11.3±0.3 a |
| 11006 | 1 | 128.4±0.1 b | 309.0±0.7 b | 554.0±2.5 b | 5.4±0.0 b |
| | 2 | 130.5±0.8 c | 309.3±0.3 b | 552.6±2.6 b | 5.2±0.1 a |
| | 3 | 122.3±0.6 a | 293.7±1.7 a | 537.4±2.7 a | 6.1±0.1 c |
| 8008 | 1 | 143.7±1.2 a | 348.5±1.5 a | 643.1±7.2 a | 4.2±0.1 a |
| | 2 | 144.2±0.5 a | 350.2±0.7 a | 654.5±1.8 b | 4.2±0.0 a |
| | 3 | 143.8±0.2 a | 349.4±0.8 a | 661.7±2.9 b | 4.2±0.0 a |
| 6510 | 1 | 167.6±0.6 b | 415.9±0.8 b | 800.8±1.2 b | 2.8±0.1 a |
| | 2 | 165.0±1.4 a | 409.6±1.7 a | 781.3±6.0 a | 2.9±0.1 a |
| | 3 | 165.6±0.6 ab | 411.1±1.9 ab | 788.8±6.6 ab | 2.9±0.0 a |
| 6515 | 1 | 220.8±0.1 b | 536.4±2.4 c | 1077.7±13.7 b | 1.1±0.0 a |
| | 2 | 207.0±3.2 a | 513.3±4.3 a | 1067.4±5.2 ab | 1.4±0.1 b |
| | 3 | 216.7±0.8 b | 527.0±0.8 b | 1044.7±7.8 a | 1.2±0.0 a |

*means within each nozzle type and droplet size parameter grouping ($D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, $V_{<100}$) followed by the same letter are not significantly different as determined using SYSTAT (Version 13, Systat Software INC., Chicago, IL)

Averaging the measured data across the three selected nozzles, insured a better estimate of the threshold for spray quality category, in absence of a calibrated set of nozzles. Comparing the results for the water only solution measured at 1.5 m/s to those previously reported by Womac (1999), which were measured in still air, shows there was very good agreement. Womac (1999) reported values of 43.8, 71.0, 90.3, 102.7 and 127.8 μm for VF/F, F/M, M/C, C/VC, VC/XC, respectively. The XC/UC category did not exist at that time. While these values are smaller than those reported here (48.4, 82.5, 106.9, 130.1 and 148.7 μm, Table 8), the differences can be attributed to sampling differences (Malvern vs Sympatec and still air versus concurrent air flow). Averaging the data across the subset of three nozzles increased the standard deviations that are added to the means that establish the upper category thresholds, as compared to individual nozzles alone. It is the authors' opinion, however, that this better represented the intended classifications, given the absence of an official set of reference nozzles. The air flow effect is also seen when comparing threshold values at 0.7, 3.1 and 6.7 m/s (Tables 8 and 9) with larger overall droplet sizes measured at the higher airspeeds, particularly with respect to the $D_{v0.1}$ and % volume < 100 μm ($V_{<100}$). These differences are a result of the greater velocity differential between the smaller and larger droplets at the lower airspeed (Frost and Lake 1981; Czaczyk 2012). At lower airspeeds, the smaller droplets decelerate after leaving the nozzle much quicker than the larger droplets. The result is a larger concentration of smaller droplets at the measurement location. This has the effect of overestimating the smaller fraction of the spray with a spatial sampling method (laser diffraction) (Frost and Lake 1981). At higher airspeeds, this differential velocity between different sizes of droplets is reduced resulting in a more accurate estimate of the true droplet size (Frost and Lake 1981). These data highlight the need for a reference standard when evaluating additional nozzles. Such a standard would insure that accurate relative classifications are made between different laboratories.

**Droplet Sizing and Classification of Additional Nozzles**

Droplet size data and classification categories for each nozzle, pressure and air flow velocity are shown in tables 10 (207 kPa) and 11 (414 kPa). All droplet size category assignments were made using the droplet size threshold data from tables 8 and 9 for both the water only and water plus NIS. Upper threshold limits were the means plus one standard deviation, as specified in S572.1 (ASAE 2009). A comparison of actual droplet size data shows the significance of air flow on the actual measured volume diameters and percent fines ($V_{<100}$). Lower 0.7 m/s air velocity always results in volume diameters that are lower than those measured at 3.1 and 6.7 m/s, with larger diameters measured as the air velocity increases. This relationship is the topic of a number of other works and is a function of both differential droplet velocity of different diameter droplets and the use of a spatial sampling method such as laser diffraction (Frost and Lake 1981; Dodge 1987; Young and Bachalo 1988; Lefebvre 1989; Arnold 1990; Spray Drift Task Force 1997; Hewitt *et al.* 2002). The relationship is, again, the reason for a relative classification standard such as S572.1. From the data in tables 10 and 11, it is important to note that for the vast

Table 8. Reference nozzle droplet size data for the water only spray solution. Volume mean diameters are presented as the mean (across all three replicate measurements of all three selected nozzles) plus one standard deviation, as this defines the upper limit of the respective ASAE droplet size category (DSC)

| Airspeed [m/s] | Nozzle | ASAE DSC | $D_{v0.1}$ | $D_{v0.5}$ | $D_{v0.9}$ | $V_{<100}$ [$\%_{vol}$] |
|---|---|---|---|---|---|---|
| | | | mean + standard deviation [μm] | | | |
| 0.7 | 11001 | VF/F | 48.4+1.5 | 116.2+0.6 | 199.0+1.4 | 37.6 |
| | 11003 | F/M | 82.5+0.5 | 188.7+1.3 | 363.1+3.4 | 15.7 |
| | 11006 | M/C | 106.9+1.3 | 280.8+4.3 | 554.3+4.1 | 8.4 |
| | 8008 | C/VC | 130.1+3.2 | 354.1+1.9 | 671.4+3.6 | 4.8 |
| | 6510 | VC/XC | 148.7+1.9 | 427.5+4.0 | 797.6+9.8 | 3.6 |
| | 6515 | XC/UC | 194.7+7.5 | 569.8+9.6 | 1115.4+19.4 | 2.2 |
| 3.1 | 11001 | VF/F | 59.9+0.6 | 125.3+1.1 | 212.4+2.0 | 32.9 |
| | 11003 | F/M | 95.5+0.6 | 221.9+1.3 | 389.8+2.3 | 11.1 |
| | 11006 | M/C | 131.3+2.1 | 328.4+4.9 | 584.6+4.3 | 5.3 |
| | 8008 | C/VC | 149.2+0.8 | 379.9+2.0 | 692.3+5.4 | 4.1 |
| | 6510 | VC/XC | 177.5+1.4 | 455.5+3.8 | 820.6+10.8 | 2.9 |
| | 6515 | XC/UC | 243.1+3.3 | 611.3+5.6 | 1171.1+8.4 | 1.5 |
| 6.7 | 11001 | VF/F | 60.2+2.5 | 130.6+4.3 | 224.0+7.6 | 31.1 |
| | 11003 | F/M | 106.0+0.7 | 241.8+1.2 | 406.0+1.8 | 8.7 |
| | 11006 | M/C | 153.9+3.6 | 354.2+6.4 | 605.7+9.8 | 3.7 |
| | 8008 | C/VC | 173.4+0.8 | 401.1+1.5 | 708.5+4.4 | 2.8 |
| | 6510 | VC/XC | 209.2+1.4 | 482.4+2.1 | 845.9+3.4 | 1.9 |
| | 6515 | XC/UC | 290.0+2.9 | 653.3+5.1 | 1187.7+25.1 | 0.8 |

Table 9. Reference nozzle droplet size data for the water plus 0.25% v/v NIS (R11) spray solution. Volume mean diameters are presented as the mean (across all three replicate measurements of all three selected nozzles) plus one standard deviation, as this defines the upper limit of the respective ASAE droplet size category (DSC)

| Airspeed [m/s] | Nozzle | ASAE DSC | $D_{v0.1}$ | $D_{v0.5}$ | $D_{v0.9}$ | $V_{<100}$ [$\%_{vol}$] |
|---|---|---|---|---|---|---|
| | | | mean + standard deviation [μm] | | | |
| 0.7 | 11001 | VF/F | 34.4+10.6 | 114.2+0.9 | 193.9+1.8 | 39.0 |
| | 11003 | F/M | 76.5+0.9 | 172.6+1.6 | 334.6+1.8 | 18.3 |
| | 11006 | M/C | 96.3+2.7 | 236.0+9.6 | 487.5+11.8 | 11.0 |
| | 8008 | C/VC | 109.5+0.8 | 299.7+3.1 | 596.7+6.0 | 8.0 |
| | 6510 | VC/XC | 128.1+3.3 | 354.2+5.1 | 713.2+4.8 | 4.9 |
| | 6515 | XC/UC | 150.7+4.6 | 447.8+15.8 | 1006.6+37.3 | 3.1 |
| 3.1 | 11001 | VF/F | 56.6+1.0 | 121.7+1.3 | 208.2+2.1 | 35.1 |
| | 11003 | F/M | 88.0+0.4 | 203.6+0.6 | 358.5+0.8 | 13.5 |
| | 11006 | M/C | 111.2+2.4 | 278.8+6.2 | 526.0+7.7 | 7.7 |
| | 8008 | C/VC | 126.1+0.8 | 327.2+2.0 | 614.9+7.7 | 5.8 |
| | 6510 | VC/XC | 141.2+1.0 | 382.6+2.6 | 747.2+10.4 | 4.5 |
| | 6515 | XC/UC | 176.1+5.0 | 483.4+9.3 | 1043.3+28.9 | 2.6 |
| 6.7 | 11001 | VF/F | 56.8+1.4 | 127.3+3.5 | 226.4+5.4 | 33.2 |
| | 11003 | F/M | 95.5+1.0 | 221.1+1.5 | 377.6+2.5 | 11.1 |
| | 11006 | M/C | 127.1+3.7 | 304.0+7.8 | 548.0+8.3 | 5.6 |
| | 8008 | C/VC | 143.9+0.7 | 349.4+1.2 | 653.1+9.1 | 4.2 |
| | 6510 | VC/XC | 166.1+1.4 | 412.2+3.1 | 790.3+9.6 | 2.8 |
| | 6515 | XC/UC | 214.9+6.4 | 525.5+10.4 | 1063.3+16.8 | 1.2 |

majority of the cases, the same classification category is defined, regardless of the air velocity measurement. The few cases that do differ, only do so by one category. Generally classification categories resulting from the water + NIS solution, are larger than the water only as a result of lower overall category droplet size thresholds (Table 8 and 9). There are difference in the volume diameters and percent fines ($V_{<100}$) between the air velocities used in this study. Simply reporting numerical values for evaluated spray nozzles or solutions without the reference nozzle data obtained under similar conditions, is not adequate and does not facilitate meaningful comparisons between laboratories. Moreover, reporting only the droplet size of tested nozzles or spray solution, without including reference nozzle data is not enough. Such reporting effectively limits the numerical data to being used as a relative measure between other nozzles or solutions evaluated at the same time and under the same conditions.

Table 10. Droplet size data and ASAE S572.1 droplet size category for tested nozzles at 207 kPa and coaxial air flow velocities of 1.5, 7 and 15 m/s for both the water only and water plus NIS reference curve data

| Nozzle | Airspeed [m/s] | $D_{v0.1}$ / $D_{v0.5}$ / $D_{v0.9}$ [μm] | $V_{<100}$ [$\%_{vol}$] | ASAE droplet size category | |
|---|---|---|---|---|---|
| | | | | water only | water + 0.25% R11 |
| AI 11003VS | 0.7 | 200.5 / 523.5 / 961.2 | 1.25 | extremely coarse | ultra coarse |
| | 3.1 | 267.0 / 594.5 / 1029.4 | 0.68 | extremely coarse | ultra coarse |
| | 6.7 | 307.9 / 631.5 / 1047.9 | 0.38 | extremely coarse | ultra coarse |
| AITT 11003 | 0.7 | 226.1 / 563.9 / 1085.5 | 0.82 | extremely coarse | ultra coarse |
| | 3.1 | 294.5 / 628.3 / 1122.1 | 0.41 | ultra coarse | ultra coarse |
| | 6.7 | 328.5 / 664.1 / 1182.5 | 0.25 | ultra coarse | ultra coarse |
| AIXR 11003 | 0.7 | 126.4 / 287.9 / 567.3 | 4.84 | coarse | coarse |
| | 3.1 | 147.6 / 342.5 / 600.8 | 3.50 | coarse | very coarse |
| | 6.7 | 171.8 / 373.8 / 635.2 | 2.20 | coarse | very coarse |
| AVI ISO 11003 | 0.7 | 181.5 / 477.6 / 901.3 | 1.34 | extremely coarse | ultra coarse |
| | 3.1 | 242.5 / 552.3 / 971.6 | 0.75 | extremely coarse | ultra coarse |
| | 6.7 | 291.6 / 606.9 / 1025.7 | 0.37 | extremely coarse | ultra coarse |
| D3-25 | 0.7 | 87.3 / 198.6 / 422.2 | 13.82 | medium | medium |
| | 3.1 | 103.7 / 240.7 / 457.5 | 8.98 | medium | medium |
| | 6.7 | 110.4 / 258.0 / 471.2 | 7.75 | medium | medium |
| D5-25 | 0.7 | 83.4 / 157.4 / 250.3 | 16.59 | fine | fine |
| | 3.1 | 83.6 / 168.9 / 283.3 | 16.03 | fine | fine |
| | 6.7 | 90.2 / 187.7 / 315.1 | 12.90 | fine | fine |
| D8-45 | 0.7 | 104.6 / 233.0 / 515.0 | 8.75 | medium | medium |
| | 3.1 | 118.3 / 288.4 / 567.1 | 6.55 | medium | coarse |
| | 6.7 | 136.4 / 327.6 / 604.8 | 4.64 | medium | coarse |
| FC-GA 11003 | 0.7 | 131.2 / 305.4 / 576.1 | 3.93 | coarse | very coarse |
| | 3.1 | 161.4 / 368.6 / 632.1 | 2.50 | coarse | very coarse |
| | 6.7 | 186.1 / 394.5 / 656.2 | 1.67 | coarse | very coarse |
| FC-TR 11003 | 0.7 | 75.7 / 160.5 / 306.7 | 18.91 | fine | fine |
| | 3.1 | 83.4 / 183.9 / 338.0 | 15.68 | fine | fine |
| | 6.7 | 88.9 / 201.7 / 354.0 | 13.19 | fine | fine |
| GAT 11003 | 0.7 | 145.1 / 314.9 / 596.9 | 2.71 | coarse | very coarse |
| | 3.1 | 171.4 / 383.5 / 655.8 | 2.08 | very coarse | extremely coarse |
| | 6.7 | 198.6 / 413.4 / 681.8 | 1.27 | very coarse | extremely coarse |
| LU 11003 POM | 0.7 | 69.8 / 152.6 / 286.9 | 21.85 | fine | fine |
| | 3.1 | 77.7 / 170.6 / 316.1 | 18.60 | fine | fine |
| | 6.7 | 87.8 / 194.2 / 340.1 | 13.73 | fine | fine |
| MD 11003 | 0.7 | 164.9 / 396.9 / 710.6 | 2.11 | very coarse | extremely coarse |
| | 3.1 | 205.5 / 455.0 / 759.3 | 1.56 | very coarse | extremely coarse |
| | 6.7 | 228.7 / 474.0 / 780.9 | 1.16 | very coarse | extremely coarse |
| TTJ 11006VP | 0.7 | 155.8 / 397.0 / 895.2 | 2.92 | very coarse | extremely coarse |
| | 3.1 | 174.5 / 460.5 / 981.9 | 2.57 | very coarse | extremely coarse |
| | 6.7 | 193.7 / 499.5 / 1044.3 | 1.84 | very coarse | extremely coarse |

Table 11. Droplet size data and ASAE S572.1 droplet size category for tested nozzles at 414 kPa and coaxial air flow velocities of 1.5, 7 and 15 m/s

| Nozzle | Airspeed [m/s] | $D_{v0.1}$ / $D_{v0.5}$ / $D_{v0.9}$ [µm] | $V_{<100}$ [$\%_{vol}$] | ASAE droplet size category | |
|---|---|---|---|---|---|
| | | | | water only | water + 0.25% R11 |
| AI 11003VS | 0.7 | 168.2 / 396.6 / 710.9 | 2.04 | very coarse | extremely coarse |
| | 3.1 | 211.1 / 456.6 / 774.1 | 1.29 | extremely coarse | extremely coarse |
| | 6.7 | 231.3 / 470.2 / 773.7 | 0.96 | very coarse | extremely coarse |
| AITT 11003 | 0.7 | 172.3 / 424.2 / 850.7 | 1.94 | very coarse | extremely coarse |
| | 3.1 | 204.8 / 482.8 / 920.1 | 1.19 | extremely coarse | extremely coarse |
| | 6.7 | 233.1 / 503.8 / 896.9 | 0.78 | extremely coarse | extremely coarse |
| AIXR 11003 | 0.7 | 105.8 / 224.9 / 457.8 | 8.41 | medium | medium |
| | 3.1 | 118.1 / 268.7 / 487.8 | 6.43 | medium | medium |
| | 6.7 | 133.0 / 297.7 / 515.3 | 4.65 | medium | medium |
| AVI ISO 11003 | 0.7 | 141.5 / 343.7 / 674.3 | 3.35 | coarse | very coarse |
| | 3.1 | 171.8 / 403.5 / 710.5 | 2.23 | very coarse | extremely coarse |
| | 6.7 | 200.2 / 438.0 / 750.6 | 1.42 | very coarse | extremely coarse |
| D3-25 | 0.7 | 68.2 / 160.0 / 328.9 | 21.24 | fine | fine |
| | 3.1 | 79.9 / 183.9 / 350.6 | 16.93 | fine | fine |
| | 6.7 | 86.4 / 200.9 / 365.4 | 14.07 | fine | fine |
| D5-25 | 0.7 | 62.6 / 132.9 / 207.5 | 26.87 | fine | fine |
| | 3.1 | 64.0 / 136.8 / 227.5 | 26.70 | fine | fine |
| | 6.7 | 69.6 / 148.5 / 247.6 | 22.96 | fine | fine |
| D8-45 | 0.7 | 91.4 / 219.0 / 509.5 | 12.29 | medium | medium |
| | 3.1 | 103.8 / 262.1 / 546.7 | 9.11 | medium | medium |
| | 6.7 | 118.1 / 292.5 / 571.2 | 6.81 | medium | medium |
| FC-GA 11003 | 0.7 | 100.8 / 229.9 / 455.9 | 9.78 | medium | medium |
| | 3.1 | 119.0 / 275.9 / 487.8 | 6.37 | medium | medium |
| | 6.7 | 134.4 / 303.3 / 512.1 | 4.71 | medium | medium |
| FC-TR 11003 | 0.7 | 56.5 / 138.1 / 271.7 | 28.54 | fine | fine |
| | 3.1 | 65.9 / 146.8 / 290.0 | 25.88 | fine | fine |
| | 6.7 | 71.5 / 162.6 / 299.7 | 21.39 | fine | fine |
| GAT 11003 | 0.7 | 106.9 / 211.3 / 415.5 | 7.99 | medium | medium |
| | 3.1 | 115.3 / 254.0 / 461.8 | 6.75 | medium | medium |
| | 6.7 | 130.5 / 286.3 / 491.6 | 4.89 | medium | medium |
| LU 11003 POM | 0.7 | 54.0 / 130.9 / 238.6 | 30.92 | fine | fine |
| | 3.1 | 63.3 / 139.9 / 266.1 | 28.20 | fine | fine |
| | 6.7 | 66.8 / 153.1 / 285.1 | 24.27 | fine | fine |
| MD 11003 | 0.7 | 140.8 / 311.1 / 573.7 | 3.37 | coarse | very coarse |
| | 3.1 | 159.9 / 352.0 / 596.1 | 2.66 | coarse | very coarse |
| | 6.7 | 181.2 / 379.0 / 620.2 | 2.03 | coarse | very coarse |
| TTJ 11006VP | 0.7 | 119.0 / 287.8 / 732.9 | 6.26 | coarse | coarse |
| | 3.1 | 126.1 / 341.1 / 794.0 | 5.75 | medium | very coarse |
| | 6.7 | 136.7 / 370.6 / 814.1 | 4.79 | medium | coarse |

## CONCLUSION AND DISCUSSION

Droplet size evaluations of spray systems are critical to understanding how changes in the system affect spray quality. Droplet size evaluations are also important in determining appropriate operational settings to be used to insure effective, efficacious, and safe application of products. Measurement of the droplet size is not a simple turnkey operation. Some thought must be given to appropriate setup and measurement methods as well as interpretation of the resulting data. Different systems and methods will generally result in different absolute droplet size data. Having differing data, then complicates the comparison or application of data from multiple laboratories. Every effort should be made to prevent the possibility of providing multiple, different droplet size data for a nozzle to an applicator. The intent of standards such as those from the BCPC and ASABE are to provide methods whereby measured data from an absolute stan-

dard allows inter-laboratory data to be compared and understood by the end users. However, even that may not be a perfect solution. Variations in droplet size between "identical" reference nozzles can further complicate or bias classification of additional nozzles and spray solutions. Care must be taken to insure that a certified set of reference nozzles are used. Careful selection, measurement and reporting of reference nozzle droplet size data, as well as the use of the standardized classification categories, can aid inter-laboratory comparisons and prevent confusion by the end user. There now are a number of laboratories conducting droplet sizing studies. Each laboratory should insure that a set of certified reference nozzles are incorporated into all droplet sizing work using the standard specified pressures and flow rates. This data should be provided as part of any data package or publication of data. There are significant differences between absolute droplet size data for the multiple measurement methods. For this reason, it is critical to report both detailed information on measurement protocols as well as droplet size data from the established reference nozzles.

## ACKNOWLEDGEMENTS

This study was supported in part by a grant from the Deployed War-Fighter Protection (DWFP) Research Program, funded by the U.S. Department of Defence through the Armed Forces Pest Management Board (AFPMB).

Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

USDA is an equal opportunity provider and employer.

## REFERENCES

Arnold A.C. 1990. A comparative study of drop sizing equipment for agricultural fan-spray atomizers. Aerosol Sci. Tech. 12 (2): 431–445.

ASAE S572.1. 2009. Spray Nozzle Classification by Droplet Spectra. Am. Soc. Agric. Eng., St. Joseph, MI., 4 pp.

Czaczyk Z. 2012. Influence of air flow dynamics on droplet size in conditions of air assisted sprayers. Atomization and Sprays (accepted to publishing on July 23rd), 9 pp.

Doble S.J., Matthews G.A., Rutherford I., Southcombe E.S.E. 1985. A System for classifying hydraulic nozzles and other atomizers into categories of spray quality. p. 1125–1133. In: Proc. Brighton Crop Prot. Conf. – Weeds. Brighton, UK, 18–21 November 1985, 1300 pp.

Dodge L.G. 1987. Comparison of performance of drop-sizing Instruments. Appl. Optics 26 (7): 1328–1341.

Dodge L.E., Rhodes D.J., Reitz R.D. 1987. Drop-size measurement techniques for Ssprays: comparison of malvern and laser-diffraction, and aerometrics phase/doppler. Appl. Optics 26 (11): 2144–2154.

Elsik C.M. 2011. Round-robin evaluation of ASTM standard test method E2798 for spray drift reduction adjuvants. J. ASTM Int. 8 (8): 1–22.

Frost A.R., Lake J.R. 1981. The significance of drop velocity to the determination of drop size distributions of agricultural sprays. J. Agric. Eng. Res. 26 (4): 367–370.

Hewitt A.J. 2000. Spray drift: impact of requirements to protect the environment. Crop Prot. 19 (1): 623–627.

Hewitt A.J., Johnson D.R., Fish J.D., Hermansky C.G., Valcore D.L. 2002. Development of the spray drift task force database for aerial applications. Environ. Tox. Chem. 21 (3): 648–658.

Lefebvre A.H. 1989. Atomization and Sprays. p. 367–409. In: "Drop Sizing Methods" (N. Chigier, ed.). Hemisphere Publishing Corporation, New York, 421 pp.

Southcombe E.S.E., Miller P.C.H., Ganzelmeier H., van de Zande J.C., Miralles A., Hewitt A.J. 1997. The international (BCPC) spray classification system including a drift potential factor. p. 371–380. In: Proc. Brighton Crop Prot. Conf. – Weeds. Brighton, UK, 17–20 November 1997, 1202 pp.

Spray Drift Task Force Study No. A95-010, Miscellaneous Nozzle Study 1997, EPA MRID No. 44310401.

Tishkoff J.M. 1984. Spray characterization: practices and requirements. Optical Eng. 23 (5): 557–560.

Womac A.R. 2000. Quality control of standardized reference spray nozzles. Trans. ASAE 43 (1): 47–56.

Womac A.R., Maynard R.A., Kirk I.W. 1999. Measurement variations in reference sprays for nozzle classification. Trans. ASAE 42 (3): 609–616.

Young B.W., Bachalo W.D. 1988. The direct comparison of three "In-Flight" droplet sizing techniques for pesticide spray research. p. 483–497. In: "Optical Particle Sizing: Theory and Practice" (G. Govesbet and G. Grehan, eds.). Plenum Press, New York, 642 pp.